

EFFECT OF RIBS AND STRINGER SPACINGS ON THE WEIGHT OF AIRCRAFT COMPOSITE STRUCTURES

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ABSTRACT

Low cost and less weight are the two primary objectives of any Aircraft structure. Efficient design of Aircraft components is therefore required to reduce cost and weight. For components with compressive loading, ribs and stringer spacing and stringer cross-section play a major role for weight efficient design. The main objective of the present work is aimed at establishing optimum stringer and rib spacing and stringer cross-section for minimum weight of buckling design driven components using FEA. The problem is formulated with flat 'skin-stringer' and 'skin-stringer-rib' panels with different stringer cross sections viz. blade, hat, I and J. Parametric studies are executed with different stringer spacings, rib spacings and stringer cross sections to study the effect of these parameters on the weight of the structure using Composite (T800class+epoxy system) material through linear buckling analysis of the FE model. Simply supported boundary conditions are used on all four edges of the plate with compressive loading. The software tools used are Hypermesh as pre and post processor and Radioss as solver.

Initially for all the stringer cross sections considered, stringer spacing is varied from 600mm to 50mm. It is found that the spacing below 120mm is stabilizing the weight. Too small a spacing will increase the number of stringers with issues in fabrication without much benefit in terms of weight. With this view point, two stringer spacing configurations viz. 150mm and 120mm are considered for further study on the rib spacing for each of the stringer cross sections stated earlier. Optimum stringer spacing, rib spacing and stringer cross sections are established quantitatively.

Keywords: composite, buckling, FEM, stringer spacing, rib spacing, stringer cross section

1. INTRODUCTION

It is always a challenge to design weight efficient aircraft structures and more so in case of composite structures with added material complexities. Compressive loaded structural members like wing top skin are designed to prevent both crushing failure and buckling failure. The buckling strength of a plate depends on the geometry of the plate and also the boundary conditions. It is largely in practice that for stiffened panels with stringers and ribs, simply supported boundary conditions are assumed. Therefore the geometry of the stiffened panel is what matters in increasing the buckling strength and hence demand for efficient geometrical arrangement like the stringer spacing, rib spacing and stringer cross sections for weight efficient design. But in practice, the design optimum spacing and cross section of stringer may not be feasible from manufacturing point of view. Also the selection of these parameters is of paramount importance in the initial phases of structural design, as

this will have the influence throughout the life of the aircraft in terms of complexity of the structure, weight and cost.

The current study is emphasized upon arriving at optimum spacing of ribs and stringers and stringer cross section for minimum weight of buckling design driven components, respecting the manufacturing constraints for a feasible design and thus forming a guide line for the selection of these parameters at the initial phases of structural design process. The present objective is met by linear static and buckling analysis of skin-stringer and skin-stringer-rib panels using FEM packages through parametric studies. The motivation for this approach comes from the fact that the solution for this kind of a problem through mathematical optimization becomes highly complicated. Also it can be seen from the literature survey that the mathematical optimization is done for a fixed configuration of stringer spacing by treating only the skin and the stringer thicknesses as design variables^{2,3,4,5}. No literature is found with respect to rib spacing studies.

2. PROBLEM DEFINITION

2.1 Geometry selection, loading and Boundary Condition

Typically in Aircraft structures, the stringer spacing adopted is in the range from 100 to 200mm and rib spacing used is around 300 to 500mm. For ‘skin-stringer’ panel, a plate width of 600 mm is considered for the study of stringer spacing. The length dimension of the plate is fixed at 300 mm which is nothing but the typical rib spacing. For study of ‘skin-stringer-rib’ panel, the width of the plate is kept equal to the previous case i.e. 600 mm. Plate length of 2000 mm is considered for studying the rib spacing. A compressive load of magnitude 2000N/mm is applied which accounts to a total load of 1.2×10^6 N for a 600mm width plate as shown in Fig. 1. Simply supported boundary conditions on all four sides of the plate are considered. The stringer cross sections considered for the study are shown in Fig. 2.

2.2 Material

T800 class carbon fiber+epoxy system is selected as the material for the present study. The properties used for this material in the analysis are $E_{11}=150$ GPa, $E_{22}=9$ GPa, $G_{12}=4$ GPa, $\gamma_{12}=0.35$, $X_T=1200$ MPa, $X_C=725$ MPa, $Y_T=Y_C=25$ MPa, $S=51$ MPa, $\rho=1.6$ gm/cc and Ply thickness=0.18mm.

2.3 Problem formulation and solution procedure

The problem is formulated as a 2D problem numerically using FEM packages. Hypermesh is used as the pre- and post-processor and Radioss as the solver. FE model is created using 2-dimensional quad elements. Composite material property is assigned using PCOMP property card and M8 material card. Simply supported boundary conditions are applied on all four sides of the plate i.e ‘Z’ is constrained on all the edges of the plate. Compressive load is applied on one edge and ‘X’ is constrained on all the nodes of the opposite edge of the plate and ‘Y’ is constrained on the middle node of this edge. FE models of ‘stringer alone’ configuration and ‘stringer-rib’ configuration are shown in Fig.3 and Fig. 4 respectively.

Tsai Hill composite failure theory⁸ is used for composite failure index, which is given by

$$F = \frac{\sigma_1^2}{X^2} - \frac{\sigma_1 \sigma_2}{X^2} + \frac{\sigma_2^2}{Y^2} + \frac{\tau_{12}^2}{S^2} \dots \dots \dots (1)$$

a value of $F < 1$ indicating ‘no failure’ of the laminate.

The governing differential equation for buckling of a symmetric laminate subjected to in-plane loading is given by¹³

$$D_{11} \frac{\partial^4 w}{\partial x^4} + 4D_{13} \frac{\partial^4 w}{\partial x^3 \partial y} + 2(D_{12} + D_{33}) \frac{\partial^4 w}{\partial x^2 \partial y^2} + 4D_{23} \frac{\partial^4 w}{\partial x \partial y^3} + D_{22} \frac{\partial^4 w}{\partial y^4} = N_x \frac{\partial^2 w}{\partial x^2} + 2N_{xy} \frac{\partial^2 w}{\partial x \partial y} + N_y \frac{\partial^2 w}{\partial y^2} \dots \dots \dots (2)$$

For Buckling strength of the panel, the following Eigen value problem is solved

$$[K + \lambda K_G] \Phi = 0 \dots \dots \dots (3)$$

In the above equation, for the lowest eigenvalue (λ) > 1, the panel is free from buckling.

Initially the plate alone is subjected to buckling analysis by monitoring the buckling factor so as to keep its value close to 1 by varying the thickness of the plate. The flow chart of the analysis procedure is shown in Fig. 5. Subsequently the procedure is repeated by adding the stringers (reduced spacing) and monitoring the weight and composite failure index. For skin-stringer-rib panel study, the procedure is repeated by adding the ribs for a chosen stringer spacing configuration. Fig. 6 shows the buckling pattern of mode 1, i.e. $m=1$ and $n=1$ and Fig. 7 shows the buckling contour of the plate for blade stringer configuration.

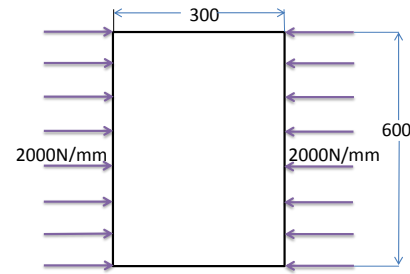


Fig. 1 Loading on the plate

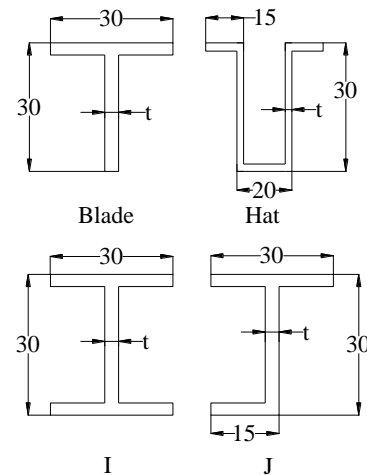


Fig. 2 Stringer cross-sections

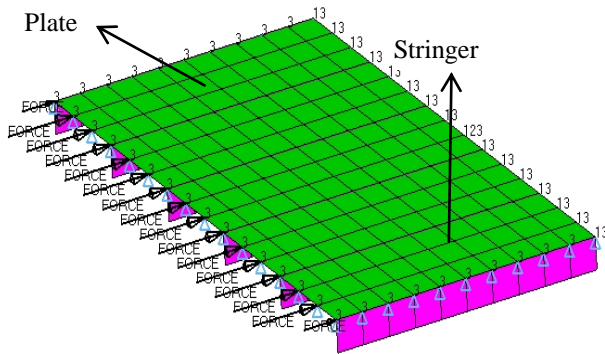


Fig. 3 FE model for plate with stringer

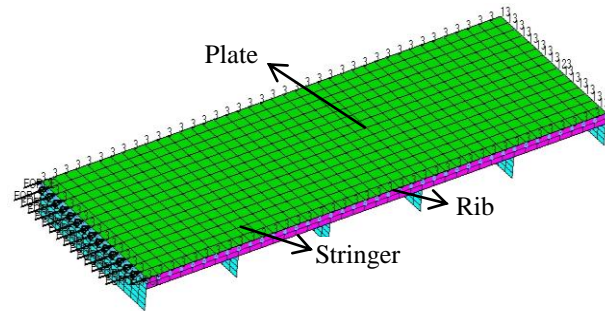


Fig. 4 FE model for plate with stringer and ribs

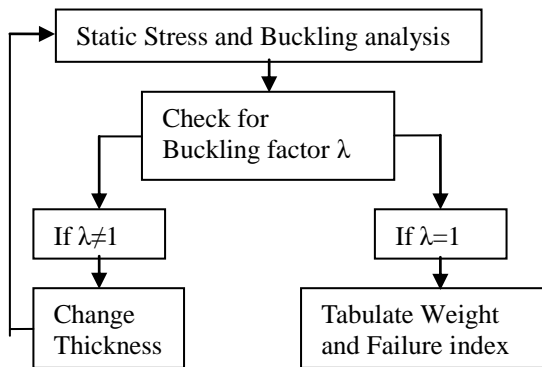


Fig. 5 Flow chart of analysis

Result : E:\arun.project\Final analysis\Arun.project\Plate with stringer+ribs\2000-600(Ribs h=90mm)\stringer spacing=120mm\result
Subcase 2 - bl - Mode 1 - F = 1

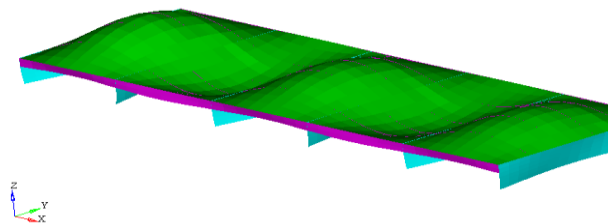


Fig. 6 Buckling pattern of mode 1

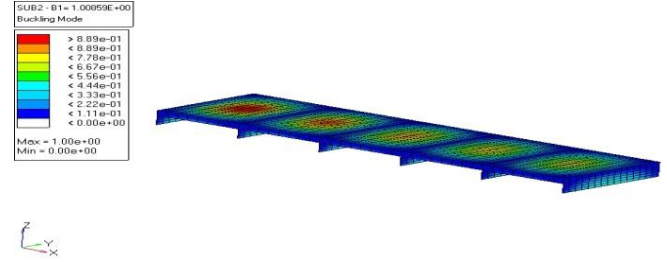


Fig. 7 Buckling contour of mode 1

2.4 Convergence Study

Convergence study is carried out for optimum element size to be used in the FE models. The study is performed only on the skin-stringer panel and is assumed valid on skin-stringer-rib panels also. From Fig. 8, it is seen that the weight is almost constant for element sizes between 5 to 20 mm for different stringer spacing and hence an element size of 10 to 20 mm is adopted in all the models.

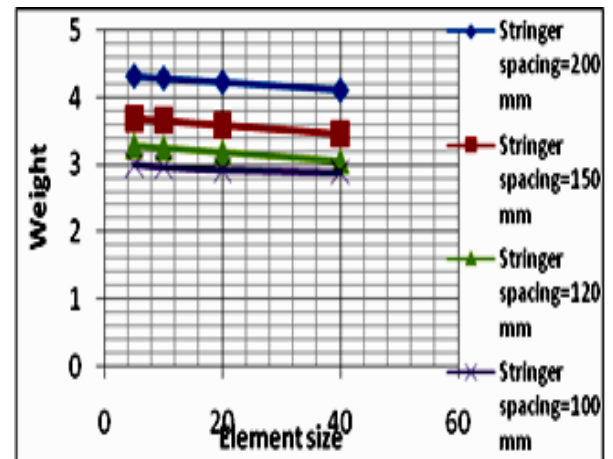


Fig. 8 Weight vs element size for blade stringer

3. RESULTS AND DISCUSSIONS

Before conducting studies of stringer spacing, rib spacing and stringer cross sections, it is extremely important to identify other parameters which may affect the end result and select them appropriately to get reliable results. The following parameters are identified as the critical ones and are evaluated to quantify them appropriately for further studies.

1. Lay-up sequence
2. Stringer thickness variation with respect to plate thickness
3. Stringer height
4. Stringer web width of hat stringer

3.1 Lay-Up Sequence

It is a practice and also a rule in design of composite structures to orient more layers in primary loading direction to exploit the directional properties of composites. Also the lay-up sequence will be symmetric and balanced about the mid-layer in order to minimize the coupling terms. The important point to be noted here is that we are looking at buckling strength of a plate and therefore the stiffness requirement in all the directions will be important instead of only in the primary loading direction. To quantify this, the following lay-up sequences are selected for the study.

- (a) 40 - 50%: $\pm 45^\circ$, 10 - 20%: 90° and remaining 0° plies
 (b) Equal no of $\pm 45^\circ$, 90° , and 0° plies – quasi-isotropic laminate

First lay-up sequence is loading direction dominant lay-up sequence wherein, 0° layer accounts for almost 50% of the laminate thickness. The percentage of plies is chosen based on the guidelines of composite laminate design. Second one is quasi-isotropic lay-up wherein the stiffness of the laminate is same in all the four directions.

Study on comparison of lay-up sequence is carried out for the blade stringer only. The stringer thickness is kept equal to skin thickness. Weight of the stiffened panel is monitored at critical buckling load. Graph of Weight is plotted against no of stringers for various stringer spacings for the two cases (a) and (b) in Fig. 9. Quasi-isotropic laminate is found to be marginally efficient than the other especially at higher stringer spacing, in terms of minimum weight. Therefore quasi-isotropic laminate is used for further studies.

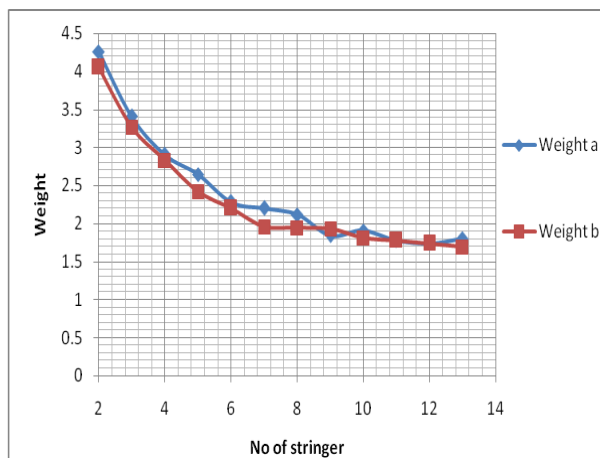


Fig. 9 Weight v/s no of stringers for different lay-up sequence

3.2 Stringer Thickness Variation with Respect to Plate Thickness

Stringer basically supports the skin in buckling and hence should have sufficient stiffness to do so. Too small a thickness of the stringer may not increase the buckling strength of the skin considerably and too large a thickness may result in weight penalty. Therefore it is logical to establish the relation between skin thickness and the stringer thickness. The studies are carried out on both blade and hat stringers as below to establish the relations.

3.2.1 Blade stringer

The stringer thickness is varied as 0.75, 1, 1.25, 1.5, and 1.75 times the plate thickness for different stringer spacing. Weight for all the cases at the critical buckling factor i.e. at $\lambda=1$ is established.

From Fig. 10 it can be seen that decreased spacing (increased no of stringers) decreases the weight of the structure for all the five cases of stringer thickness. It is also evident that the weight is minimum for stringer thickness equal to plate thickness as compared to the other cases. For further studies on blade stringer, thickness is kept equal to skin thickness.

As I and J stringers also have a single web as in blade stringer, the thickness for these stringer cross sections are also kept equal to skin thickness for studies on spacing and cross sections.

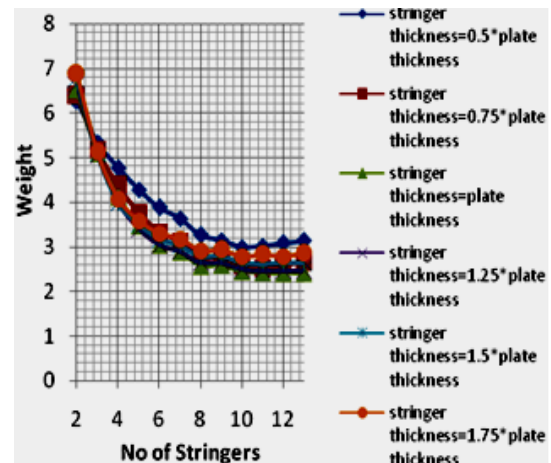


Fig 10. Weight v/s no of stringers for various stringer thicknesses for blade stringer

3.2.2 Hat stringer

Hat stringer is different geometrically, compared to other stringer cross sections that it has two webs unlike others. To establish the web thickness w.r.t skin thickness, two cases are studied viz. equal to plate thickness and 0.5 times the plate thickness for critical buckling factor.

Weight is found minimum for stringer thickness = $0.5 \times$ plate thickness as seen from Fig. 11. Therefore stringer thickness = $0.5 \times$ plate thickness for hat stringer is considered for further studies on stringer height variation.

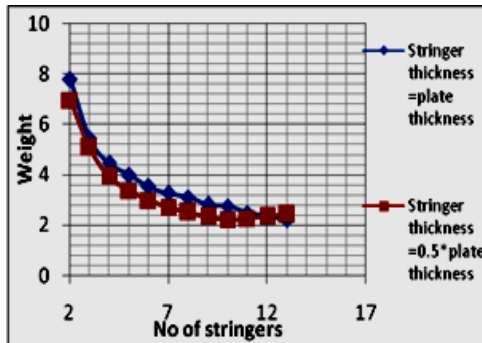


Fig. 11 Weight v/s no of stringers for various stringer thickness for hat stringer

3.3 Effect of stringer height

The stringer height will also have a considerable effect in increasing the buckling strength of the panel. The following studies are carried out for blade and hat stringers

3.3.1 Blade stringer

By taking stringer thickness equal to plate thickness, height of the blade stringer is varied as 25 mm, 30 mm, 32 mm, 35 mm, 37 mm and 40 mm for two cases of stringer spacing viz. 150mm and 120mm. Weight for all the cases at the critical buckling load is monitored.

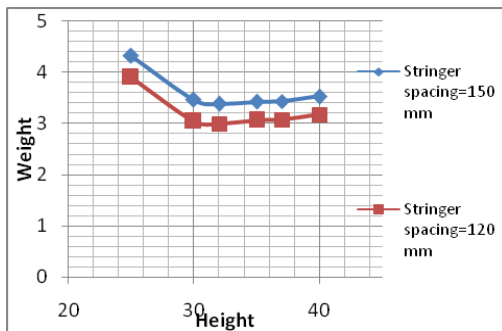


Fig. 12 Weight v/s Height for various stringer spacing for blade stringer

From Figure 12 it is evident that weight is minimum and is almost constant for stringer heights varying from 30mm to 37mm. Stringer height of 30 mm is considered for further studies on stringer cross sections and stringer spacings.

For I and J section stringers also, the height of the stringer is kept at 30mm.

3.3.2 Hat stringer

By taking stringer thickness equal to $0.5 \times$ plate thickness, height of the hat stringer is varied as 25 mm, 30 mm, 35 mm, 40 mm, 45 mm and 50 mm for two cases of stringer web width viz. 10mm and 20mm and two cases of stringer spacing viz. 120mm and 150mm. Weight for all the cases at critical buckling load is monitored.

From Fig. 13 it is clear that weight is minimum for stringer height (web height) equal to 30mm. Further, the weight is minimum for web width equal to 20mm compared to 10mm. Therefore stringer height of 30mm and web width of 20mm are considered for further studies on stringer cross sections and stringer and rib spacing.

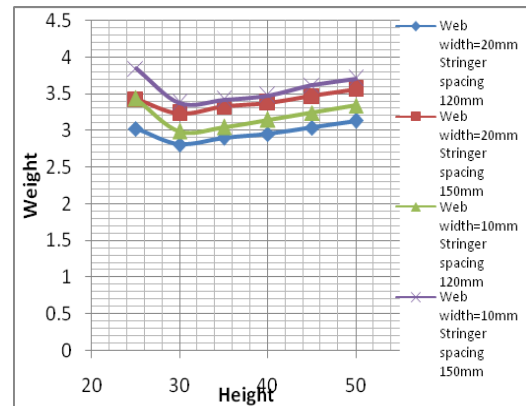


Fig 13 Weight v/s Height for various stringer spacing for hat stringer

3.4 Effect of different stringer cross section

With the major parameters influencing the buckling strength of the stiffened panel established quantitatively for their optimum values, the static strength and buckling studies are performed for different stringer cross sections stated earlier viz. blade, hat, I and J. The stringer cross section is expected to influence the weight of the buckling design driven components because of their differences in bending and torsional capabilities. Weight of the skin-

stringer panel is monitored for different stringer cross sections at the critical buckling factor, $\lambda=1$.

While the buckling factor is kept close to 1, the composite failure index is also monitored so as to facilitate prediction of potential crushing failure of the laminate.

From the results for different stringer cross sections at the critical buckling load, the graph of weight is plotted against no. of stringers in Fig. 14. Fig. 15 shows the plot of composite failure index with number of stringers.

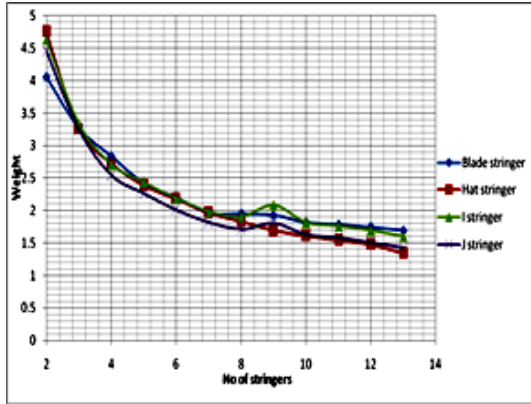


Fig. 14 Weight v/s no of stringers for different stringer cross sections

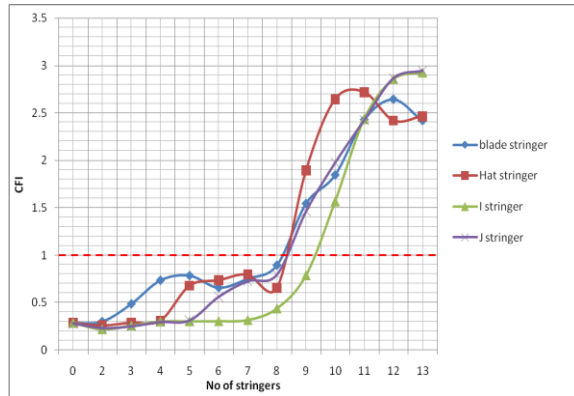


Fig. 15 Composite failure index v/s no of stringers for different stringer cross sections

From Figure 14, it can be seen that decreased spacing (increasing no of stringers) decreases the weight of the structure. Also the weight starts stabilizing for stringer spacing below 120mm.

From Fig. 15, it is evident that the CFI goes beyond 1, as the spacing becomes less than 85mm. Also the CFI is close to 1 for stringer spacing between 150mm and 85mm at buckling factor equal to 1.

But for stringer spacing below 100mm, though there is not much benefit in terms of weight as can be seen from the graph, there are additional complexities in fabrication viz.

- More number of stringers means more number of tools required for fabrication Both of these basically increase the man- hours required and additional complexities for detail design because of less space available between the stringers
- More cost and time for design and fabrication because of the complexities

Based on the above quoted reasons two economical stringer spacings both in terms of minimum weight and fabrication aspect viz. 150 mm (5 stringers) and 120 mm (6 stringers) are selected as the design cases for rib spacing studies.

3.5 Stringer-rib configuration

In the parametric studies for rib spacing also, all four different stringer cross sections are considered.

3.5.1 Effect of rib thickness with respect to plate thickness

The rib thickness is varied with respect to plate thickness by taking rib thickness equals 0.25, 0. 5, 0.75, and 1.0 times the plate thickness for stringer spacing of 120mm and 150mm. The weight for all the cases at the critical buckling factor is monitored.

From Fig. 16, it can be seen that rib thickness equals 0.5*plate thickness has the minimum weight compared to the other three cases and hence is considered for further studies on ribs spacing.

3.5.2 Effect of ribs spacing

For stringer spacings of 120 mm and 150 mm, ribs are added in succession to study the effect of ribs spacing and arrive at the optimum spacing. Plots of weight v/s no. of ribs and CFI v/s no. of ribs are shown in Fig. 17, Fig. 18 and Fig. 19, Fig. 20 respectively at critical buckling factor.

From Fig. 17 and Fig. 18, similar trend is seen as was the case with the stringer spacing i.e decreased spacing (increasing no of ribs) decreases the weight of the structure. The weight is minimum for stringer configuration of 120mm spacing as compared to 150 mm spacing configuration. The CFI value is also below 1 indicating a non-failure of the laminate in all the cases as observed in Fig. 19 and Fig. 20.

For I and J stringer configuration, the rib spacing below 400mm stabilizes the weight of the structure and thus can be considered as the optimum rib spacing. For hat stringer configuration, the optimum rib spacing is 330mm as the rib spacing below this is not helping in reducing the weight; on the contrary it is increasing the complexity of the structure with more number of ribs. For blade stringer configuration, the rib spacing has to be as low as 285mm to stabilize the weight. The above differences can be attributed to the fact that the loading considered here is only a compression loading. The buckling strength for pure compression loading is majorly influenced by the flexural rigidity of the stringer cross sections. I and J stringers are having higher flexural strength because of additional flanges at the extremities followed by Hat and Blade stringers. Perhaps for a shear buckling strength, hat stringer may turn out to be more efficient than the other cross sections because of its higher torsional stiffness.

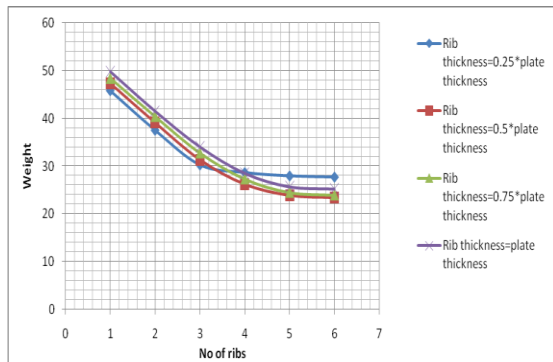


Fig 16 Weight v/s no of Ribs for different Rib thickness

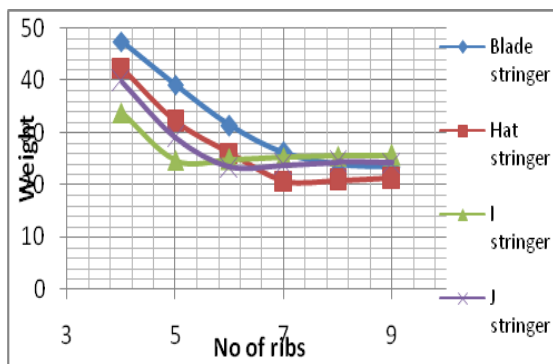


Fig 17 Weight v/s no of ribs for different stringer cross-section for stringer spacing=150mm

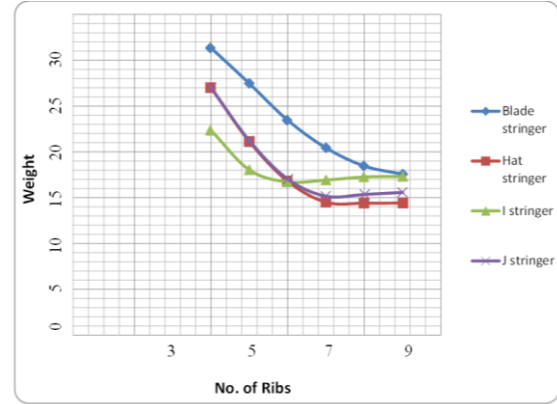


Fig 18 Weight v/s no of ribs for different stringer cross-section for stringer spacing=120mm

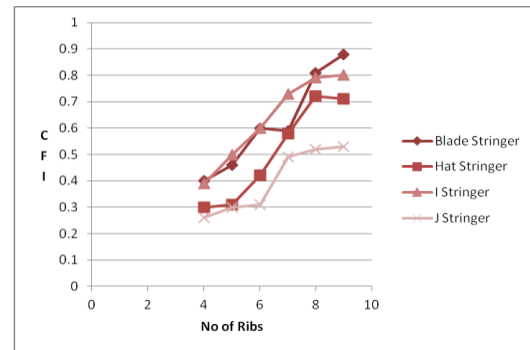


Fig 19 CFI v/s no of ribs for different stringer cross-section for stringer spacing=150mm

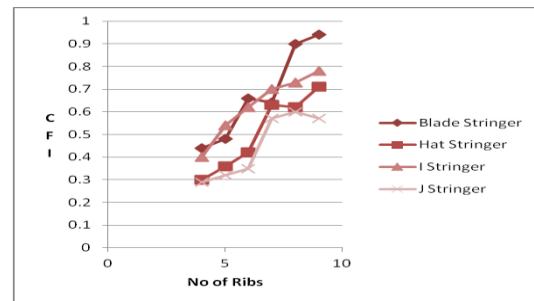


Fig 20 CFI v/s no of ribs for different stringer cross-section for stringer spacing=150mm

4. Summary and Conclusions

Parametric studies on stringer spacing, stringer cross section and ribs spacing are carried out to arrive at the optimum values of these parameters. The following parameters are considered optimum design parameters for weight efficient design and relatively less complex structure.

- For blade stringer, stringer thickness must be equal to plate thickness
- For hat stringer, stringer thickness must be $0.5 \times \text{plate thickness}$.
- Stringer height of 30mm is efficient for both blade and hat stringers.
- Stringer spacing below 120mm is optimum in terms of weight efficient structure. But spacing below 100mm is uneconomical because of complexity of the structure due to more number of parts without any benefit in terms of weight. Therefore a stringer spacing around 120mm is economical in terms of weight, complexity and cost.
- The optimum rib spacing is around 400mm for I and J stringers, 330mm for Hat stringer and 285mm for Blade stringers for weight efficient structure.

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